



Emission estimates and air quality simulation on Lombardy during lockdown

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Abstract

This paper illustrates the study carried out by ARPA Lombardia to quantify the variation in daily emissions of the main pollutants and their impacts on air quality in Lombardy during the anti-COVID-19 lockdown between the end of February and the end of May 2020. A methodology for emission estimates was developed over Lombardy for this purpose and later was extended to larger areas: the Po-basin, (LIFE PREPAIR 2020) and the entire Italy (PULVIRUS 2021). In this study, the daily emissions estimates were derived by combining data from air emission inventory of Lombardy and a set of indicators that allowed to update the estimates and describe the temporal and spatial variations of the emission sources. The calculation of emission variation was conducted for all the main pollutants (PM₁₀, NH₃, NO_x, SO₂, NMVOC) and the greenhouse gases; then, the impact on air quality concentrations was simulated by the chemical and transport model FARM, that also allows to track secondary particulate and its variability in time and space on the basis of nonlinear processes and weather conditions. The estimated emission reduction, compared to the expected average value in the absence of anti-COVID-19 measures, daily varies depending on pollutants and is mainly affected by reductions in road traffic emissions and an estimated increase in domestic heating emissions. Simulations confirm strong reductions of NO₂ atmospheric average concentrations, slightly variations of PM₁₀ averages and a potential growth of tropospheric ozone.

Keywords Model simulation · Air quality · Emission reduction · COVID-19

Introduction

Lombardy is the most populated region of Italy, placed in the Po-basin, in the north of the country (Fig. 1). The map in Fig. 1 depicts zones and agglomerates for the assessment of air quality according to the European and national legislation. In particular, the territory is characterized by three main urbanized areas (Milano, Bergamo, and Brescia), surrounded by densely urbanized areas. The Alpine area covers the largest part of the north of Lombardy.

The progressive adoption of containment measures due to the spread of COVID-19 led to variations in the emissions from different sectors. Two periods can be identified: the first one, 23/02/2020–08/03/2020, characterized by the first containment measures on limited areas and the second

one, from the 9th of March, characterized by more drastic measures throughout the region. May, on the other hand, saw a gradual easing of these measures. The evolution of the main national measures to deal with the spread of the virus is reported below:

- 23 February 2020: Decree-Law no. 6 of 23 February 2020, which ordered containment measures in areas where at least one positive case has been found (DL.6 23/02/2020).
- 23 February 2020: Ordinance of the Ministry of Health in agreement with the Lombardy Region, which ordered, among other things, the closure of schools of all levels (Ord. Min. Sal. 23/02/2020).
- 1 March 2020: Decree of the President of the Council of Ministers, which ordered restrictive containment measures in 10 municipalities of the Lodi area, the epicentre of the contagion, including the ban on movement and further containment measures, such as the suspension of activities and events, in Lombardy (DPCM 01/03/2020).

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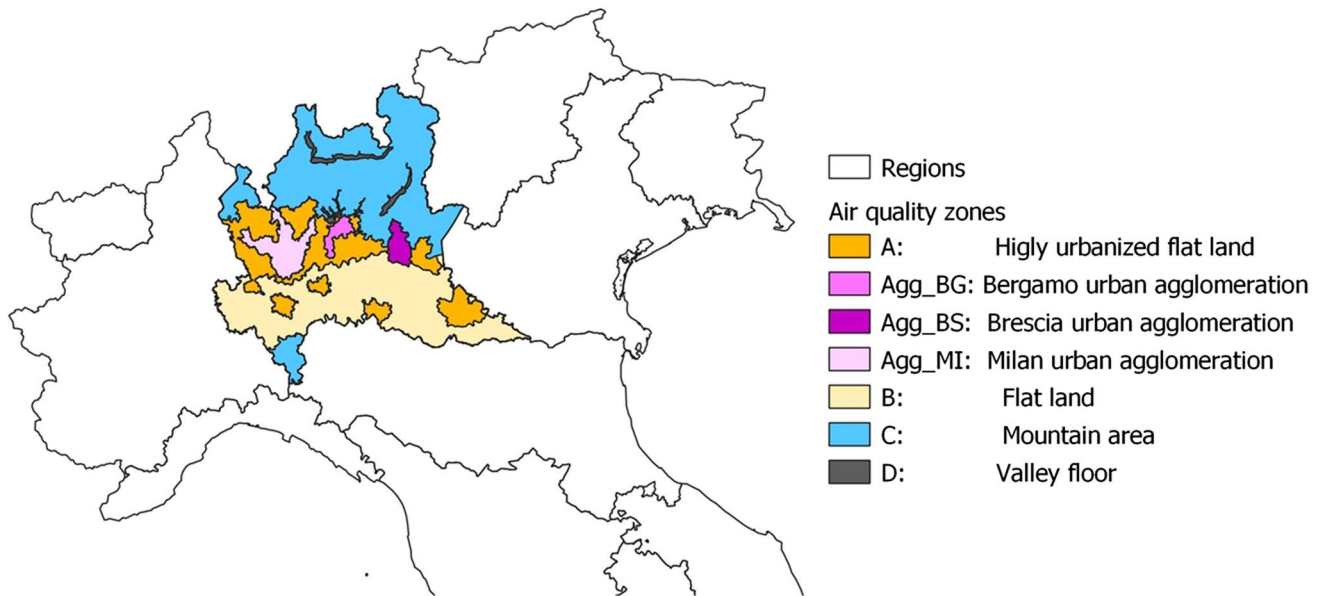


Fig. 1 Lombardy region placement in north Italy, with evidence on administrative boundaries and main air quality zones (Regione Lombardia 2011)

- 8 March 2020: Decree of the President of the Council of Ministers, which ordered restrictive containment measures, including the ban on travel, throughout Lombardy (DPCM 08/03/2020).
- 9 March 2020: Decree of the President of the Council of Ministers, which extended the provisions of the Prime Ministerial Decree of 8 March 2020 to the entire national territory (DPCM 09/03/2020)
- 22 March 2020: Decree of the President of the Council of Ministers, which suspended most of the industrial and commercial production activities (DPCM 22/03/2020).
- 25 March 2020: Decree-Law no. 19 of 25 March 2020 which included measures to face epidemiological emergency (DL.19 25/03/2020)
- 1 April 2020: Decree of the President of the Council of Ministers extending the containment measures until 13 April 2020 (DPCM 01/04/2020).
- 26 April 2020: Decree of the President of the Council of Ministers, measures for the containment of the Covid-19 emergency in the so-called "phase two" (DPCM 26/04/2020).
- 17 May 2020: Decree of the President of the Council of Ministers, implementation of Decree-Law 16 May 2020, n. 33 and in force from Monday 18 May (DPCM 17/05/2020).

As a matter of fact, starting from the identification of the first cases of COVID-19 disease, between the end of February and the first week of March, a progressive enforcement of measures of containment was adopted, starting from local

areas up to the whole region and national territory determining the lockdown of a greater number of activities.

Emission estimates

Since the beginning of the more drastic phase of lockdown, ARPA Lombardia provided a series of update on the estimates of daily emission for the main pollutant due to restriction measures. This activity is documented by a series of reports covering the period between February and May 2020 (Marongiu et al. 2020). These reports were considered and discussed by studies and evaluations (Piccoli et al. 2020; Riva and Lonati 2021; Lovarelli et al. 2020), and the methodology for emission estimates was extended on larger areas: Po-basin (LIFE PREPAIR 2020) and the Italian State (PULVIRUS 2021).

Daily emission estimates are calculated by combining data of the emission inventory of Lombardy updated to 2017 with a set of indicators chosen with the aim to update the estimates for 2019 and to describe the degree of variation of the emission sources due to lockdown. The calculation was conducted for all the main pollutant and greenhouse gases of the emission inventory detailed for source classification (SNAP 3 levels classification) and fuel type.

The variation in daily emissions of the main pollutants on the whole territory of Lombardy and on the main air quality zones, due to the anti-COVID-19 measures, was based on data available from documents and/or databases owned by ARPA, Lombardy Region or public. The estimated emission reductions, compared to the expected

average value in the absence of measures, vary daily and depending on the pollutants.

The methodology implemented to estimate emission variation, as for the emission inventories, was based on a linear relationship between the activity (A) of the evaluated source and the related emission (E). The daily emission (E) in 2020 for a certain pollutant of a specified source and fuel type consumption was estimated by applying the following relationship:

$$E_{2020,\text{pollutant,activity,fuel,day}} = E_{2017,\text{pollutant,activity,fuel,year}} \times \frac{A_{2020,\text{day}}}{A_{2017,\text{year}}}$$

Emissions for each day of 2020 were calculated as a function of the 2017 annual emissions and the ratio between the daily value of the indicator of activity and its annual value in 2017. The core of the methodology is the ratio of the daily value of the activity in 2020 and its total amount in 2017; the sum of the terms of the equation for all day of 2020 will bring to a relation where the total emission of 2020 is equal to the emission of 2017 corrected by the ratio of annual value activity between 2020 and 2017. Daily values $A_{2020,\text{day}}$ can be calculated from the sources (e.g., number of landing and takeoff in airports, electric energy, or natural gas consumed, ...) or by daily coefficients disaggregating annual emissions into finer data up to daily profiles with an approach common in global atmospheric research (Crippa et al. 2020) and in the elaboration of emission input in chemical and transport models. The methodology was applied by the following general criteria:

- The starting point was the identification of *key sources* that, potentially, could have undergone significant variations on the base of lockdown and of their relative weight on the 2017 inventory.
- For each key source, the possible activity indicators were catalogued, and, where these were not available, the so-called “proxy variables” were used. Proxies are considered as tracers that are assumed to have a trend related to the indicator. To give an example, daily average temperatures was elaborated to profile the trend of fuel consumption in the heating sector.
- Each key source (uniquely identified by a SNAP code and a fuel type) has been associated with an activity indicator or proxy.
- For all remaining sources, emissions were kept at the same level as estimated in the 2017 regional emission inventory. Daily emissions were calculated applying standard or average time profiles to annual emissions.

Production activities and industry

This group includes sources from the energy, industrial, and production sectors, related to both large and small factories.

They were analyzed according to the indicators obtained on national level and detailed day by day for: electricity consumption obtained by the Italian national grid system operator (TERNA 2020) and natural gas transportation by the national largest transportation network (SNAM 2020) with specific attention to industry daily consumption and total volume distributed. Figure 2a shows a significant reduction in total electricity and industrial natural gas consumption and a relatively lower reduction in total natural gas consumption. The total natural gas burned in heating systems was calculated based on the comparison of the heating degree days between 2020 and 2017. Data relating to the operation and the amount of energy produced by the thermoelectric power plants of Lombardy was acquired from the regional CEMS Network (Continuous Emissions Monitoring System) showing a relative substantial decrease of electricity production in May.

By the information of CEMS Network, Lombardy cement production shows a decrease compared to 2017; in April, the regional plants were practically stopped, and only in May 2020, they resumed production. In the case of glass industry, production indicators would show a decrease in May, while in April, there was an increase. The daily variation of these industrial indicators can be affected by general trends in the industry between 2017 and 2020, rather than to effects due to the measures related to COVID-19.

Heating

This sector encompasses the emission from domestic and tertiary sector heating. For both these sources, the trend of average temperatures is an indicator in calculating the daily heating demand. It was assumed that the daily thermal energy consumption for heating could be estimated from data relating to energy indicators from energy balance (ARIA 2017) and the heating degree days (HDDs) for each municipality in Lombardy. The daily value of HDD is the positive differences between room temperature, conventional 20 °C, and the daily average temperature out of the buildings. The annual HDD are calculated as the sum for all the days of the thermal season. The annual and daily HDDs were available from ARPA Lombardia according to the calculation performed by the air quality modelling suite.

The daily energy demand in 2020 was estimated by the following equation, updating data from 2017:

$$A_{2020,\text{day}} = \sum_{\text{municipality}} \frac{HDD_{2020,\text{municipality,day}}}{HDD_{2017,\text{municipality,year}}} \times A_{2017,\text{year}}$$

This equation allowed to estimate the daily regional consumption for heating updated to 2020 in a business-as-usual scenario, representing what it would be without the lockdown. This scenario was compared with an estimate of the consumptions due to restrictions introduced in 2020, assuming a greater

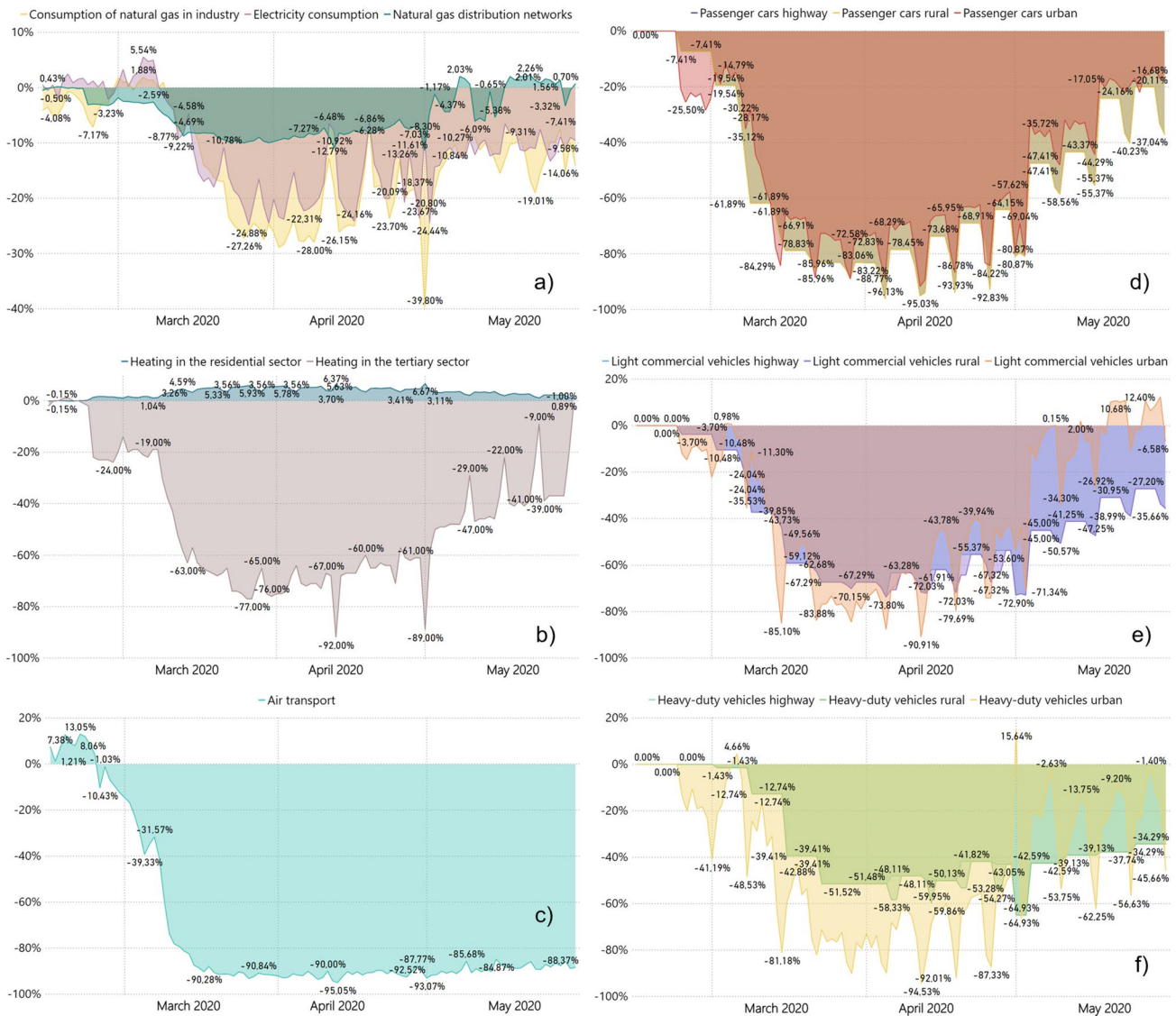


Fig. 2 Trend analysis of the main activity indicators used for the daily emission calculation and daily emission variation: **a)** natural gas and electricity consumption, **b)** heating demand, **c)** aircraft movements, **d)** passenger car fluxes, **e)** LCV fluxes, **f)** HDV fluxes

domestic presence and a collapse in tertiary sector consumptions. Available daily data for Lombardy of COVID-19 Community Mobility Report by Google (Google LLC, 2020) was considered to define the variation of presence between homes and workplaces. For domestic heating, the indicators G_{index} was corrected by the average number of family components in Lombardy, set to 2.25 (ISTAT 2020a, b; ASR 2017), to obtain an estimate of the maximum number of heating systems involved, and by the average number of working hour $h_{working}$ in a day, set to 8.

$$\frac{A_{2020,day,lockdown}}{A_{2020,day}} = 1 + \left(\frac{G_{2020,index,day}}{nc_{family}} \times \frac{h_{working}}{24} \right)$$

For the specific case of the heating in the tertiary sector, no correction on hours and number of family component was used.

In this methodology, the energy consumption calculated from the average municipal temperatures and aligned with the energy balance of the regional emission inventory was then corrected considering the variation in domestic presences reported in the Google report on COVID-19 for Lombardy. According to this report, domestic presences recorded a maximum increase of about 45% and the presences in the workplace a maximum decrease of 92%. Figure 2b shows the estimates on heating increase in domestic sector and the decrease of heating in tertiary sector.

Table 1 reports the monthly energy indicators estimated for the reference year 2017 detailed for the main

Table 1 Monthly energy consumption in PJ for different typologies of fuels burned in energy industries and in non-industrial sector for year 2017

Month	Combustion in energy and transformation industries							Non-industrial combustion plants			
	Coal	Refinery gas	Gas oil	LPG	Biomass	Natural gas	Fuel oil	Gas oil	LPG	Natural gas	Biomass
March	0.13	3.1	0.0007	0.0001	0.9	12.8	0.1	0.8	0.8	37.8	3.0
April	0.12	3.0	0.0005	0.00003	0.5	10.5	0.1	0.4	0.4	17.7	1.6
May	0.14	3.2	0.0004	0.00001	0.1	11.2	0.1	0.1	0.2	7.7	0.6

Table 2 Monthly mileage for vehicle and road type expressed in 10⁶ km for year 2017 (buses are included in heavy vehicles)

Month	Passenger cars	Passenger cars	Passenger cars	Light-duty	Light duty	Light duty	Heavy duty	Heavy duty	Heavy duty
	Highway	Rural	Urban	vehicles	vehicles	vehicles	vehicles	vehicles	vehicles
				Highway	Rural	Urban	Highway	Rural	Urban
March	758.68	2654.69	2469.92	75.47	199.66	621.33	106.64	131.98	135.38
April	855.09	2616.14	2389.23	71.66	234.70	598.85	97.56	153.38	130.41
May	878.35	2688.01	2466.03	71.06	197.33	605.46	93.99	123.57	131.43

fuel typologies in energy and non-industrial combustion. The non-industrial combustion sector encompasses domestic and tertiary sector heating and clearly shows the seasonal trend on heating demand. Biomass consumption in the energy sector shows a similar seasonal behaviour, accounting mainly the emissions of district heating plants.

Road transport

In Lombardy since several years, the program Move-In was activated for monitoring more emissive categories of vehicles (Regione Lombardia 2020b, a, c). A black box, installed on the vehicle, allows to detect the real distances driven through a satellite connection and a dedicated technological infrastructure. In 2020, more than ten thousand vehicles were monitored by this system, allowing to calculate the average distances made every day by cars, light vehicles for freight transport, and heavy vehicles. The reduction in daily journeys, compared to those of the period 13/1–16/2, was used to calculate the reduction of urban emissions (Fig. 2d, e, f). Data from the Italian National Roads Corporation (ANAS, 2020) shows the change in mobility index (IMR) detected in Lombardy in the months of March, April, and May 2020 compared to the same months of 2019 for all vehicles and for heavy vehicles only. These indicators were used to calculate the variation in monthly extra-urban and motorway emissions (Fig. 2d, e, f). The overall weekly IMR trend across the entire national network was used to weekly modulate the monthly emission reductions.

Table 3 Number of landing and takeoffs in different Lombardy airports for year 2017

Month	Linate	Malpensa	Orio al Serio	Montichiari
March	9639	13,465	6458	686
April	8606	14,825	6760	625
May	9906	15,728	7288	912

Table 2 reports the indicators of the monthly mileage for vehicle category and road typologies estimated from the emission inventory of Lombardy for 2017.

Air transport

Daily airport emissions were calculated from the 2017 annual emissions modulated according to the daily number of movements at Malpensa and Linate airports (landings and take-offs: LTO) compared to the total LTO of 2017 (Fig. 2c).

The monthly total number of landing and takeoffs in the airports of Lombardy in 2017 is shown in Table 3.

For the estimation of the number of movements in the 2020 no-Covid scenario, the following procedure was followed:

1. calculation of the average number of movements per day of the week at Linate and Malpensa airports in the period 11/01–16/02/2020 assuming they represent the situation of February 2020 in the no-Covid scenario.
2. calculation of the average number of movements per day of the week at Linate and Malpensa airports detailed for the months of February, March, April, and May 2017.

The number of movements per day of the week in March, April, and May for the no-Covid 2020 scenario was calculated by multiplying the values calculated in point 1 by the ratio between the values calculated in point 2 and the values calculated for February 2017 for the same day of the week: e.g., LTO no-Covid Tuesday May 2020 = LTO no-Covid Tuesday February 2020 \times LTO Tuesday May 2017 / LTO Tuesday February 2017. In the case of days in the 2017 period with no data, a comparison was made with the information made available by the pan-European organization dedicated to supporting European aviation (EUROCONTROL 2020).

Agriculture

Daily emissions were estimated during the period of interest as daily profiles for manure spreading and average profiles for all other activities related to the sector, including emissions from agricultural machinery.

The annual emissions of NH_3 , estimated in the 2017 regional emission inventory for Lombardy, encompass all the sector of manure management. On this amount, it is possible to select the emission of NH_3 related to the animal categories of cattle, fattening pigs, sows, laying hens, and poultry. This subset of the emission inventory can be further detailed considering the different phases

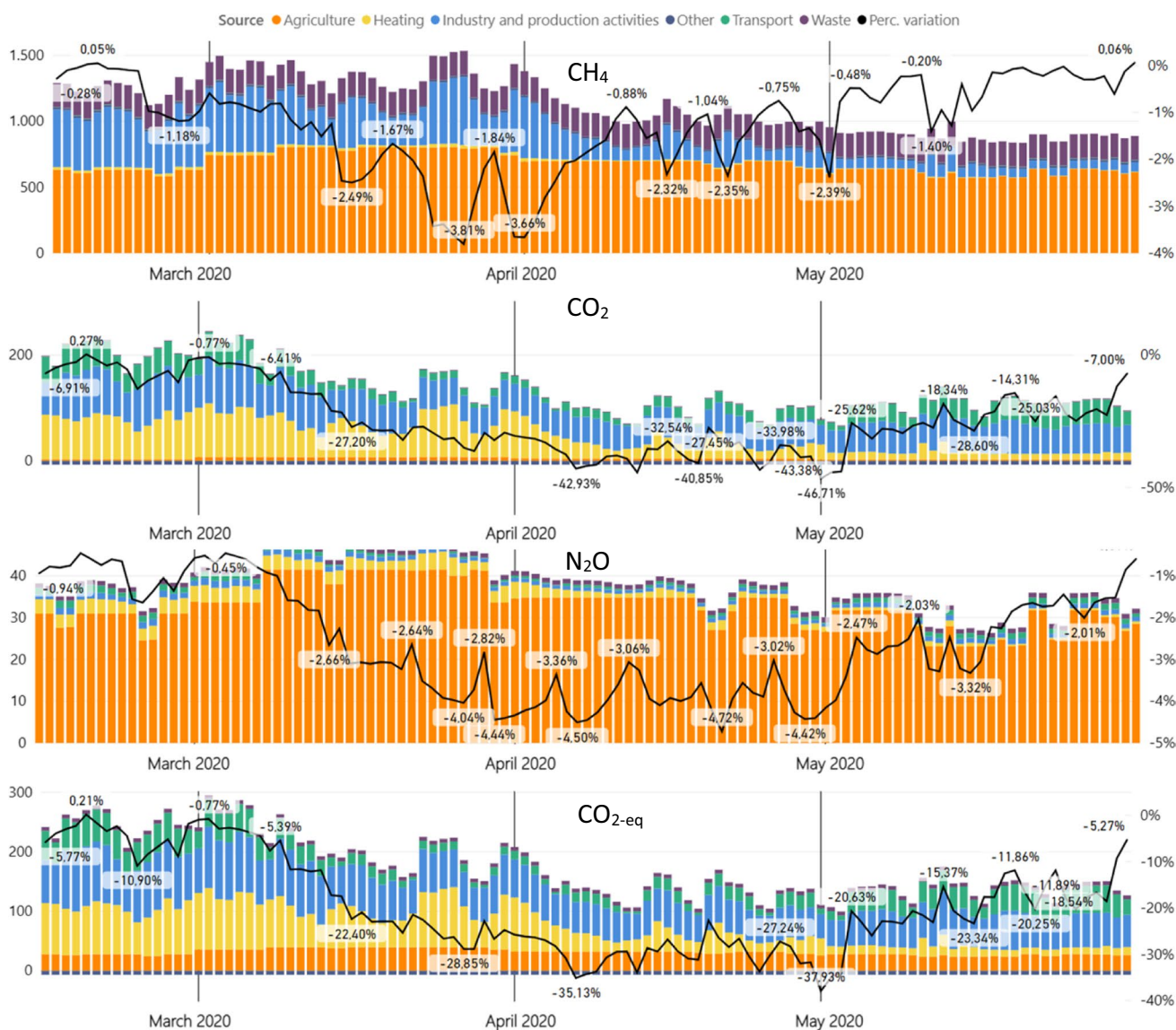


Fig. 3 a Daily regional emission of greenhouse gases detailed for emission source expressed in kt/day for CO_2 and $\text{CO}_2\text{-eq}$ and in t/day for N_2O and CH_4 in 2020 and percentage estimation due to social distancing actions in 2020. **b** Daily regional emission of atmospheric

pollutant detailed for emission source and expressed in t/day during 2020 and percentage estimation due to social distancing actions in 2020

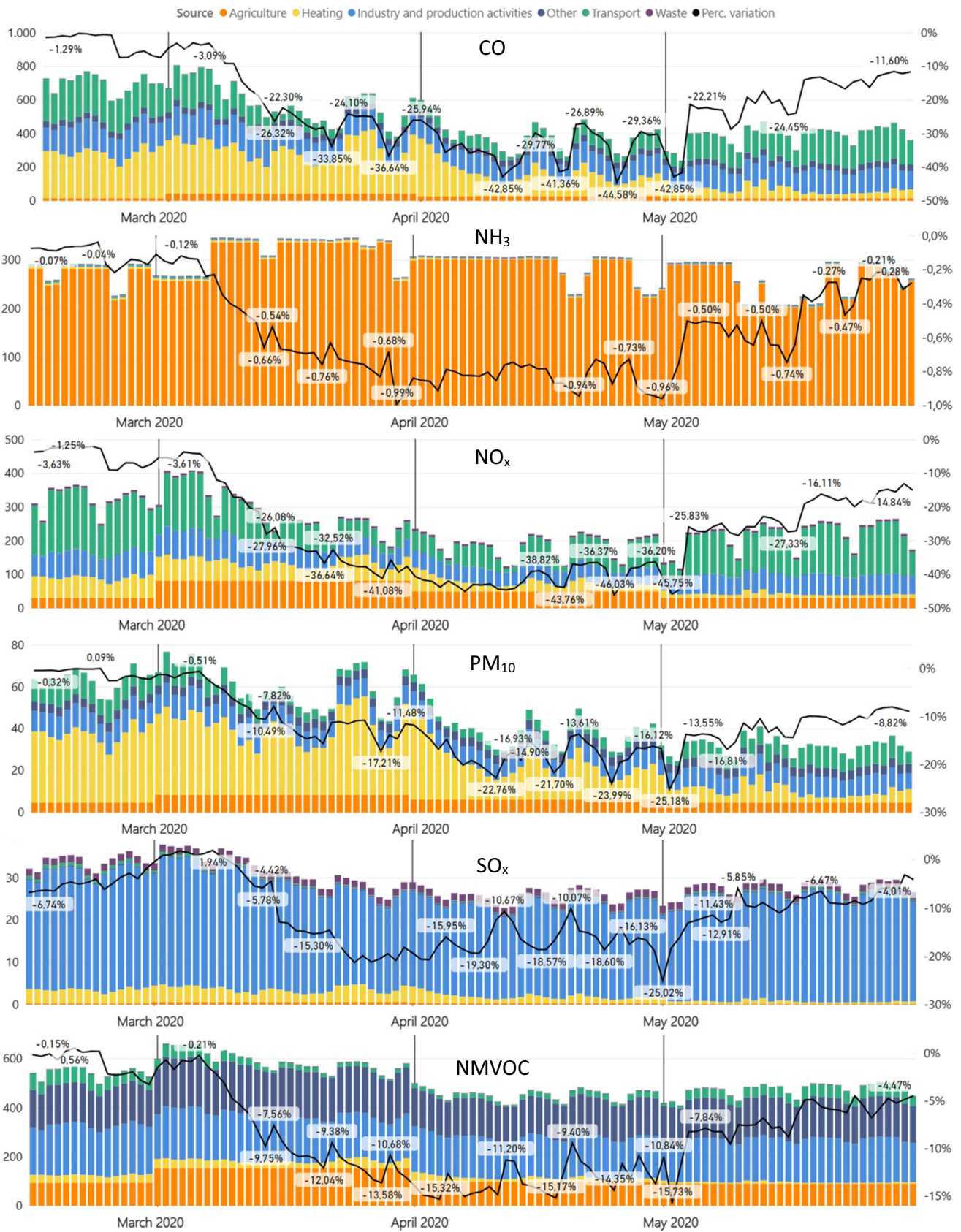


Fig. 3 (continued)

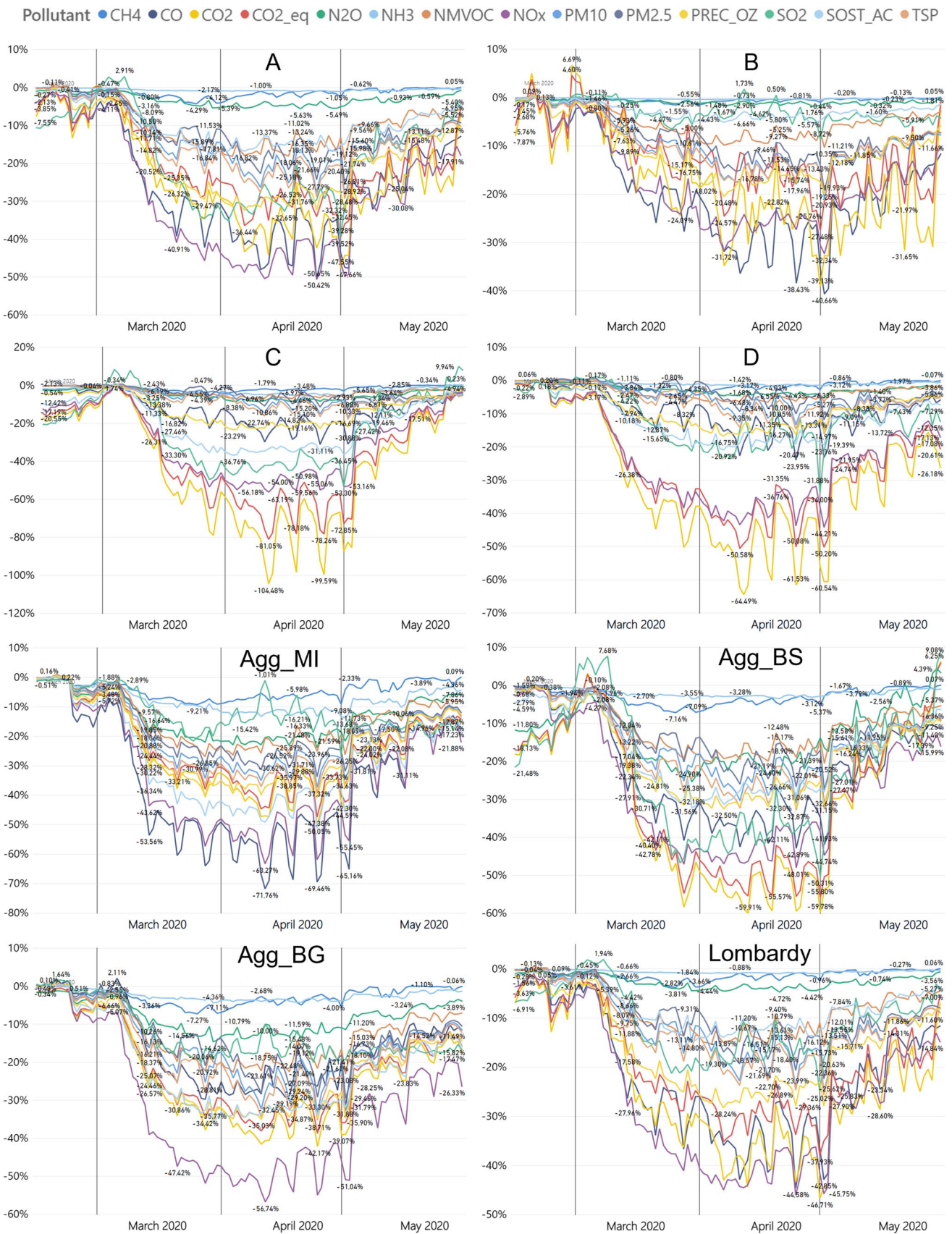


Fig. 4 Pollutant emission variation due to social distancing for different zone in Lombardy

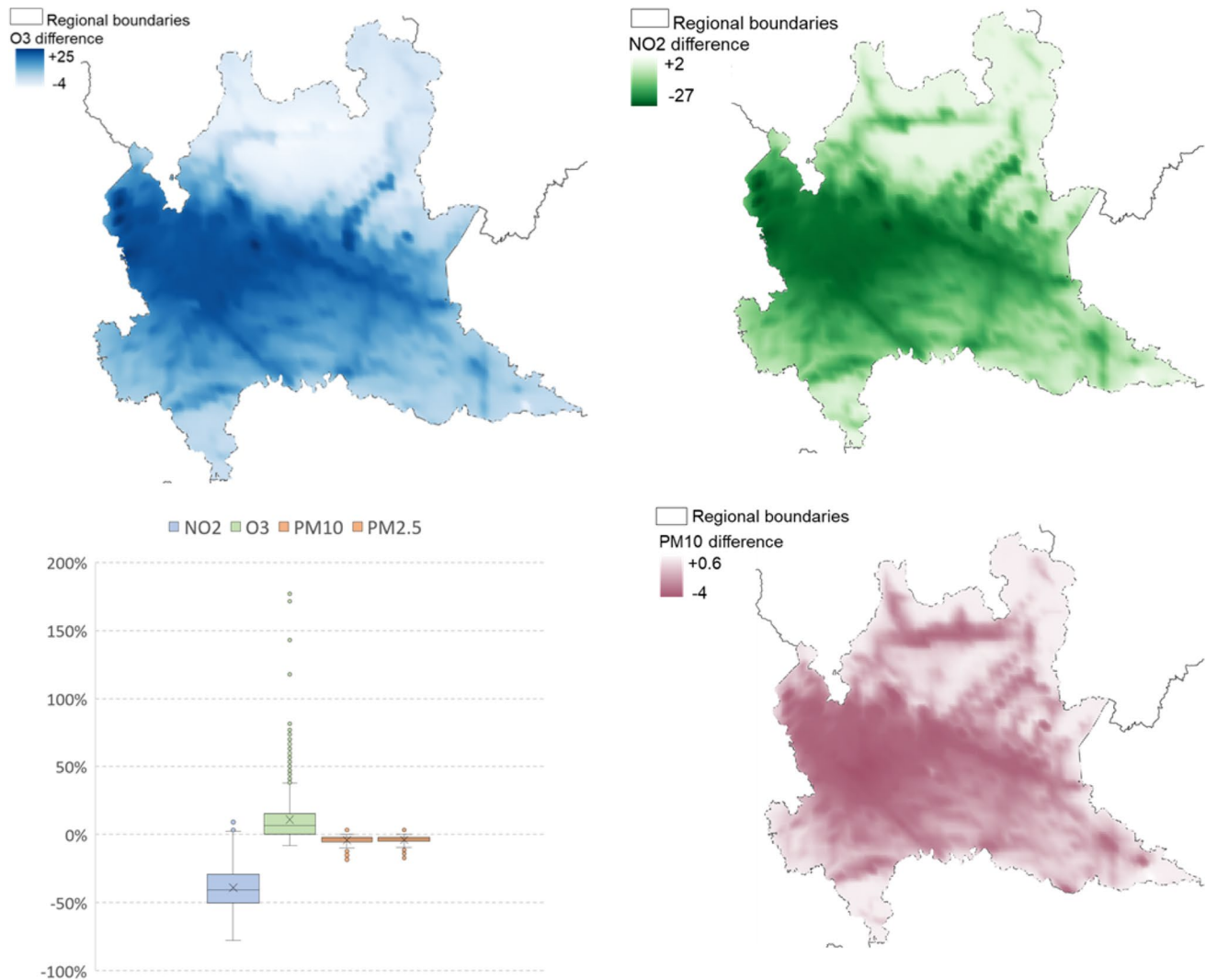


Fig. 5 Atmospheric average concentration difference between COVID and BAU scenarios; NO₂ and O₃ are expressed in ppb and PM₁₀ in $\mu\text{g m}^{-3}$. Boxplot of the percentage variation for the calcula-

tion grid point of the concentration of atmospheric pollutants in Lombardy between COVID and BAU scenarios

of manure management: housing, storage, and spreading using the information provided by the Italian Informative Inventory Report (ISPRA 2019). After calculating the regional emission for each of these three phases, the daily emissions from housing and storage were then considered constant throughout the year, while the emissions due to spreading were more detailed considering further variables.

The manure spreading depends on whether it is possible to proceed with the practice of distribution, as established for the different areas of the regional territory (Directive 91/676/EEC). For the months of November and February, manure spreading is regulated by the issue of nitrate bulletins by the Lombardy Agency for Agricultural and Forestry Services (ERSAF 2020), edited according to meteorological trends. Manure spreading is prohibited

between 1 December and 31 January, except for the publication of extraordinary bulletin, and it is forbidden on rainy days and those immediately following. The daily profile of emissions due to manure spreading was calculated considering the prohibitions, bulletin of 2020, and rainy days occurred on Lombardy.

Waste

The regional CEMS Network provided the quantities of waste incinerated by plants in Lombardy. Data analysis shows that the amount of waste burned in March 2020 decreased compared to the same period of 2017. This indicator will have to be examined in relation to its daily variation and the fact that the variations could be mainly due to general trends in the sector in comparison between the

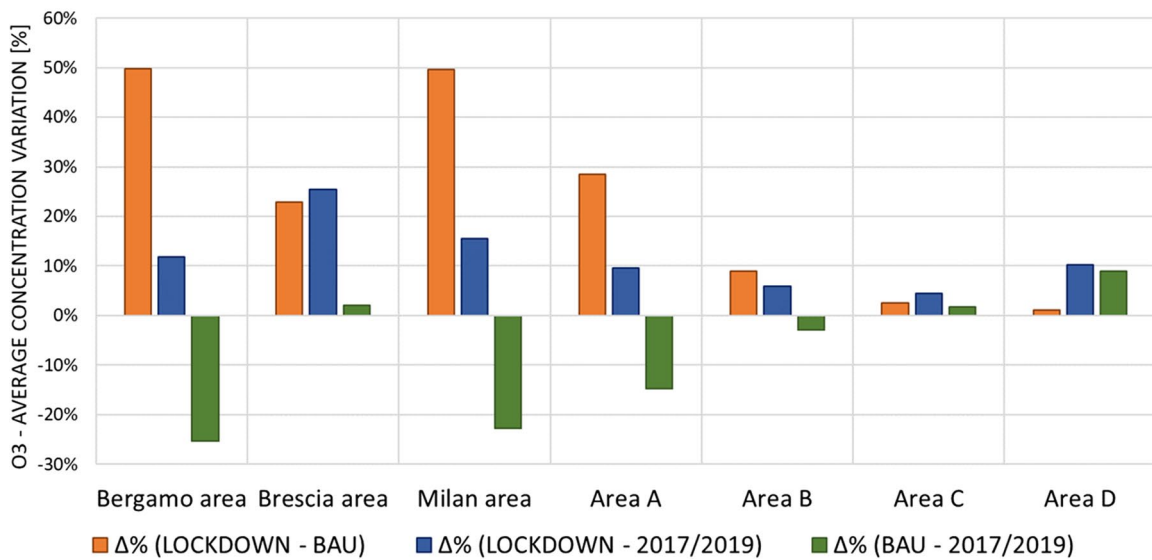
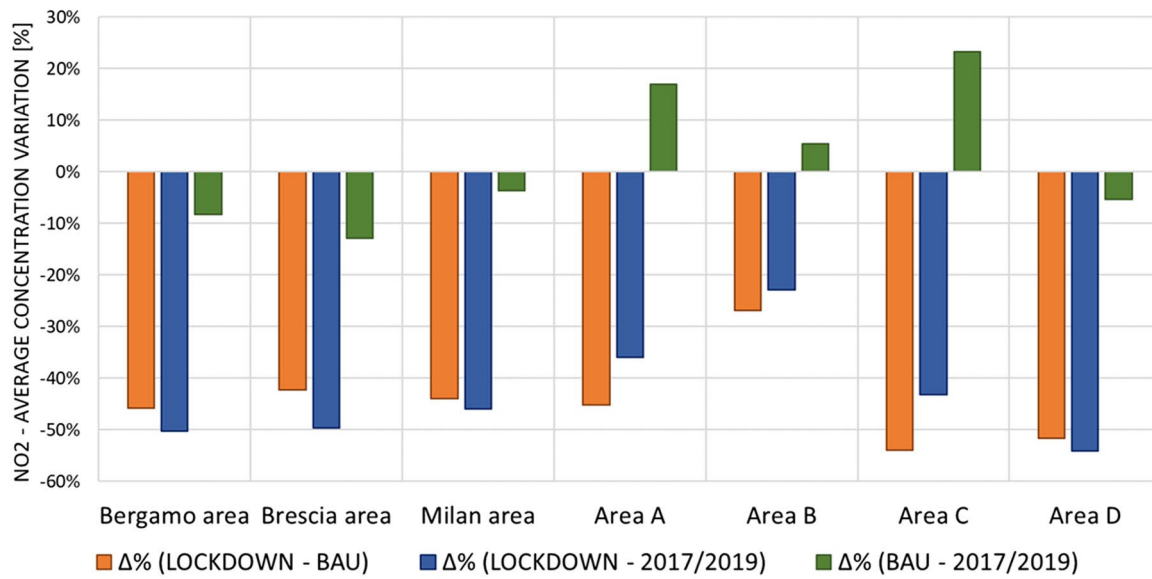
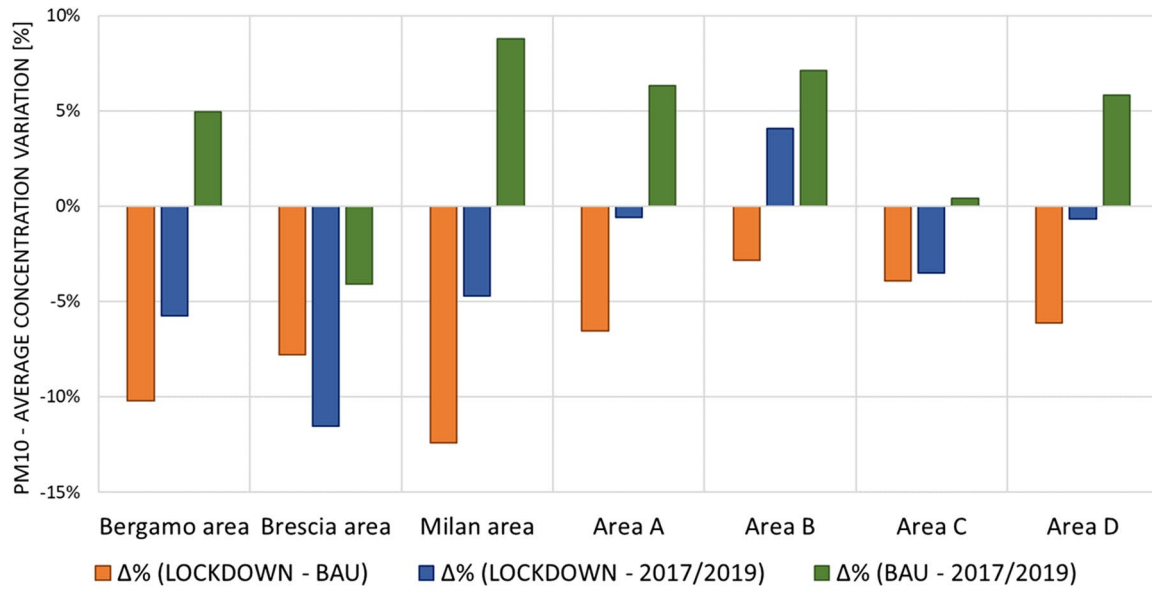


Fig. 6 Comparison between post-processed simulated values to measurements and the average of measured data in the period 2017–2019. Data refer to areas and agglomerations identified by air quality zoning of Regione Lombardia (ARPA Lombardia 2020b, a, c; Regione Lombardia, 2011)

situation of 2017 with 2020 rather than to effects due to the measures relating to COVID-19 or to effects on the waste cycle that will be evident late and not when the measures come into force.

Other

This category includes all the sources not considered in the previous ones. The only source for which a variation was considered was linked to atmospheric emissions from cremations that underwent significant variations related to the COVID widespread.

The methodology used to calculate the number of daily cremations in the period of the COVID-19 emergency was built starting from the number of deaths published by Italian National Institute of Statistics reporting daily values for provinces (ISTAT 2020b). The number of daily cremations estimated during the COVID measures was calculated by multiplying the number of deaths published by ISTAT with the percentage of national cremation (about 30% of cremations compared to other funeral services) published by the Italian Association of Funerary Service (SEFIT 2020). The same methodology was used to calculate the number of daily cremations in Lombardy in the absence of COVID measures. The daily trend analysis of the indicator shows that the cremation plants during the COVID period reached their maximum capacity (Regione Lombardia 2015) in the middle of March. This trend decreased towards the end of April, while in February, the number of cremations was aligned with the daily cremation data in the absence of measures.

Results on time resolved emissions in Lombardy during 2020

The resulting emissions obtained by the approach described above are reported in Fig. 3a and b. In the graphs, the bars show the daily emissions of the main pollutants for the group of sources described in the previous chapter (industry, heating, transport, agriculture, waste). The lines compare the total emissions with the emissions that would have been estimated in the absence of limitation measures. In Fig. 3a, CO_{2-eq} is calculated by means of the global warming potential (GWPs), according to IPCC 4th Assessment Report, equal to 1, 25, and 298, respectively, for CO_2 , CH_4 , and N_2O (IPCC, 2007). Percentage changes are calculated as:

$$(E_{2020} - E_{2020_baseline})/E_{2020_baseline}$$

where E_{2020} stays for emission calculated in lockdown period and $E_{2020_baseline}$ stays for emissions calculated for the same period of E_{2020} , but in the absence of anti-COVID-19 measures. It can be observed that the main reduction in emissions is estimated for the pollutant mainly emitted by traffic sources, reasonably affected by the drastic reduction of mobility. Pollutants mainly emitted from agriculture do not show significant variation as for NH_3 , CH_4 , and N_2O . These two latter also contribute to contrast the reduction of emissions of CO_{2-eq} which is driven by the reduction of primary emissions of CO_2 .

Figure 4 illustrates the daily percentage changes in total emission per pollutant detailed by air quality zone (Regione Lombardia 2011). In the graphs in Fig. 4, the different areas are defined as reported in the map in Fig. 1. For the areas of the valley floor, the territory considered was approximated to the entire extension of the municipal territory. It should be noted that the indicators referring to the emission variation for each zone refer to the entire region and are not detailed by zone. Accordingly, the emission evaluation must be considered indicative, and its representativeness decreases as the geographical detail increases.

Air quality simulations

The modelling system used for the scenario simulations is ARIA Regional, developed by AriaNET srl (<https://www.aria-net.it/it/>) and applied at the U.O. (organizational unit) air quality modelling and inventories of the Environmental Monitoring Sector of ARPA Lombardia. The chemical and transport model (CTM) is the Eulerian FARM model (Flexible Air quality Regional: <http://www.farm-model.org/>) that can treat the main chemical-physical processes of formation and removal of primary and secondary pollutants, as well as transport and dispersion by wind action and atmospheric mixing. FARM is used by several regional environmental protection agencies and other national bodies. The main computational elements preparing the main inputs to the model are:

1. processors for meteorological measurements;
2. diagnostic model for the reconstruction of wind, pressure, temperature, and humidity fields;
3. model for the estimation of the parameters describing atmospheric turbulence, for the determination of the dry deposition rate of gaseous pollutants, and for the determination of the closing constants of the Eulerian equations;
4. module for the elaboration of emission inventories and the preparation of the emission input to the FARM model;

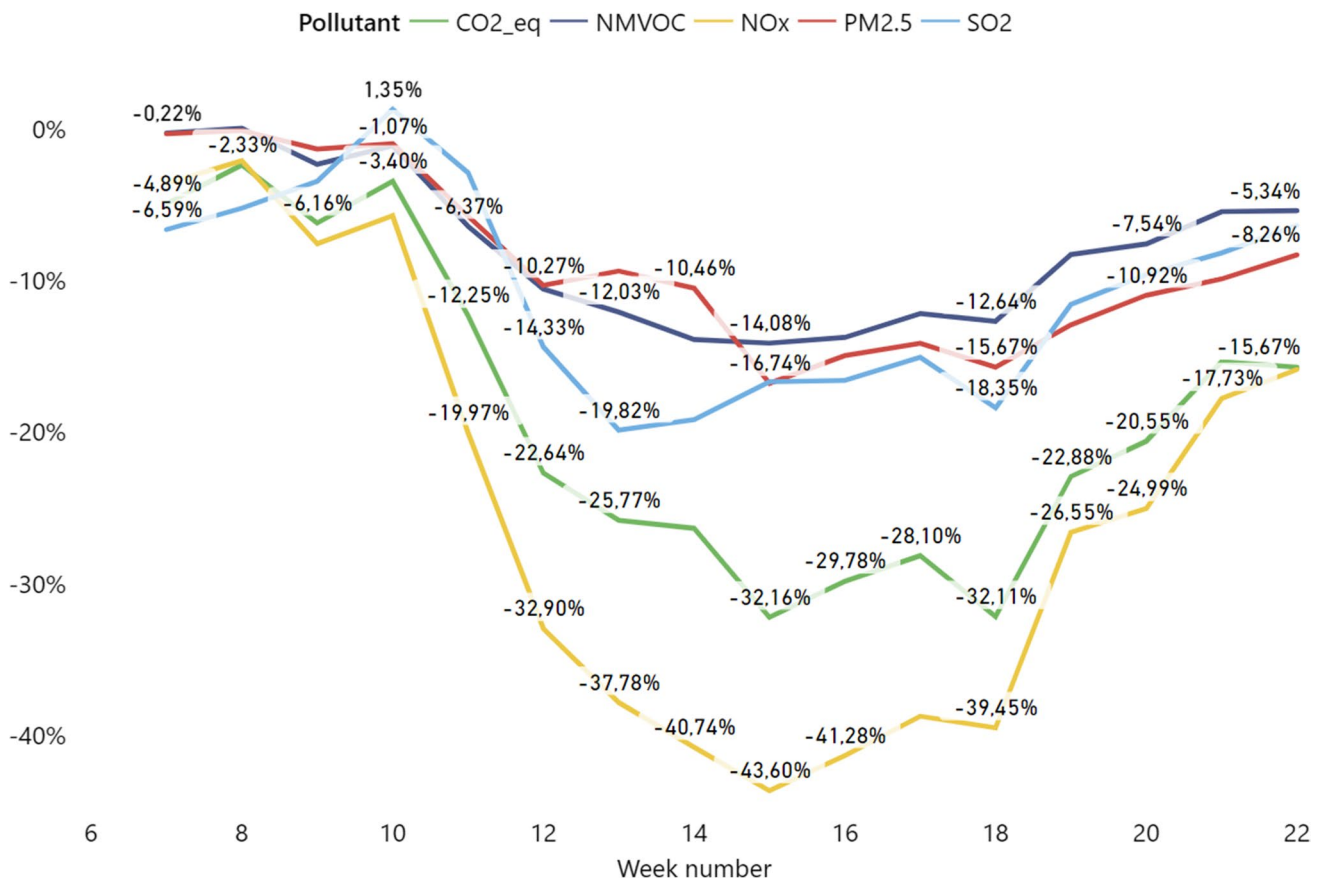


Fig. 7 Pollutant emission weekly variation due to social distancing in Lombardy during 2020

5. modules for the preparation of the initial conditions and the contour to the FARM model relying on the regional air quality database and the fields simulated on a continental scale by the CHIMERE model.

The modelling system was applied to a calculation domain of $236 \times 244 \text{ km}^2$ centred on Lombardy (for qualitative information see Fig. 1), with a grid of $4 \times 4 \text{ km}^2$ and 13 vertical levels extended from 10 to around 6000 m of altitude.

The emission input in the BAU scenario (business as usual) considered the local emission inventory (provided at municipal level) referred to 2017 and developed by the IN.EM.AR system (INEMAR, 2020), the Italian national inventory of ISPRA 2012 (<https://www.isprambiente.gov.it/it/attivita/aria-1>) disaggregated at provincial level for the surrounding Italian regions, and the EMEP 2010 emissions dataset for emissions in Switzerland. The emission scenario for the lockdown period was developed by applying the daily emission variation coefficients obtained as illustrated in the previous paragraphs to the local emission inventory, while the emissions on areas outside Lombardy were left unchanged from BAU scenario. This simplification was introduced to fast evaluate the effects on air

quality in Lombardy, where lockdown measures were introduced before than the rest of Italy. Besides, the possibility of extending the reduction rates estimated in this study to nearby regions has been investigated with local emission inventory compilers, but a certain number of dissimilarities in emission profiles emerged: i.e., noticeable differences in heating demand among the regions of the Po valley and differences in the mix of fuels adopted. The activities performed in the PREPAIR project show in detail the differences in emission reduction rates among the diverse areas of the Po-basin domain (LIFE PREPAIR 2020). The simulation domain adopted in this study is focused on Lombardy, and it is commonly adopted for near-real time air quality modelling. The most populated areas of the region are placed in the middle of the domain (Fig. 1), and it can be safely assumed that these areas will be less affected by the emissions of the surrounding regions. Further investigations about this assumption, however, will be possible through air quality simulations over the entire Italy (PULVIRUS 2022).

Emissions not deriving from chimneys of large industries required a process of spatial disaggregation on the model grid, obtained with the aid of CORINE land cover ed. 2012.

The meteorological fields for the period (01/03/2020–31/05/2020) were reconstructed by assimilating data collected from a subset of meteorological stations of local networks and from the radio-soundings of Milano Linate airport to the outputs of the European Centre for Medium-Range Weather Forecast (ECMWF) hi-res model; the simulated data were treated as vertical pseudo profiles for each point of the model grid by the mass-consistent meteorological interpolator Swift. The parameters of atmospheric turbulence and the deposition speeds of the pollutants were then estimated with the SurfPRO processor. For an extensive characterization of the meteorology of the period, it is possible to refer to the report produced within the Prepair project (LIFE PREPAIR 2020); here, it may suffice to report that March was a typical spring month in the Po Valley, with some weak disturbances, mostly of Atlantic origin, alternated to windy episodes followed by phases of high-pressure and stable conditions, the most extended of which took place around the midst of the month (at the beginning of the simulated period). April started with an unusual cold spell, driven by a north-eastern flow, which determined lower-than-usual temperatures and strong stability, occasionally interrupted by windy days. In the second half of the month and during May, a pattern of sunny and stable periods alternated to the transit of short-lasting disturbances was registered, except for a more structured episode of diffused heavy rain caused by a Mediterranean cyclone between the 15th and the 19th of May.

The boundary and initial conditions were derived from the daily processing of outputs of the Prev'air system (Continental CHIMERE) and were used as such in both simulated scenarios.

The pollutants examined are nitrogen monoxide (NO), nitrogen dioxide (NO₂), tropospheric ozone (O₃), and particulate matter (PM₁₀); their concentrations in air were elaborated hourly between 15/03/2020 and 03/05/2020 for both scenarios. Figure 5 shows the variation of average concentrations of NO₂, PM₁₀, and tropospheric O₃ in the simulated period. It can be clearly seen that higher reductions are estimated for NO₂ and lower variations are simulated for PM₁₀. On the contrary, the estimated reduction of emissions seems to determine a potential growth of tropospheric ozone.

The box-plots in Fig. 5 represent the variations estimated during the lockdown period for all the grid point of the simulation domain and confirm an important decrease of NO₂ averages and a very slight variation of atmospheric concentration of PM₁₀ and PM_{2.5}.

The simulated concentrations in the two scenarios, C_{BAU} and $C_{lockdown}$, were then post-processed by means of the following equation:

$$M_{BAU} = M_{lockdown} + M_{lockdown} \times (C_{BAU} - C_{lockdown}) / C_{lockdown}$$

where $M_{lockdown}$ are the actual measured data during the lockdown period and M_{BAU} are the reconstructed, hypothetical concentrations that could have been measured without the limitations imposed. Results in Fig. 6 confirm the decrease of NO₂ average concentrations in Lombardy during lockdown. This trend is well reproduced in all the different zones of the region, both with respect to the BAU scenario and the average of measured concentrations in the years 2017–2019. Tropospheric ozone average concentrations show a potential increase (Fig. 6) during lockdown with a higher relevance in the most urbanized areas and a relatively poor impact moving to rural areas. As stated by the map and the box plot in Fig. 5, average concentration of PM₁₀ does not vary significantly. In evaluating those results, though, it cannot be forgotten that the 2020 lockdown took place mostly in spring, a period characterized by greater variability of meteorology, thus increasing difficulties in comparing atmospheric concentrations over different years.

Conclusions

The emissions reductions calculated in this work are comparable with results obtained by other studies reported in scientific literature. Guevara et al. (2021) quantify the reductions in primary emissions caused by COVID-19 lockdown in some European countries for the main source categories (energy industry, manufactory industry, road traffic, and aviation) and for main pollutants (NO_x, SO_x, PM_{2.5}, NMVOCs). During the most severe weeks of lockdown, the study calculates an average emissions reduction of 33% for NO_x, 7% for SO_x, and 7% for PM_{2.5} in 30 European countries. More than the 85% of total reduction can be attributed to road transport. These emission reductions reach higher values, 50% for NO_x, 14% for NMVOCs, 12% for SO_x, and 15% for PM_{2.5}, in the countries where more restrictive measures were adopted such as Italy. Le Quéré et al. (2020) estimate a reduction in global CO₂ emissions due to COVID-19 lockdown, evaluating an average daily global CO₂ emissions reduction of 17% in April 2020 with respect to the mean 2019 levels. Sectors that contributed most significantly to emissions reductions are surface transport, power generation, and industry. Figure 7 depicts the estimation on emission variation on week base. The results of this study seem agree with the above-mentioned references.

Emission estimates identify week number 15 (6–12 April 2020) as the most severe week of lockdown for of regional primary NO_x, PM_{2.5}, CO_{2-eq} and NMVOC emissions, where reduction is respectively: 44%, 17%, 32%, and 14%. In the case of SO₂, the maximum decrease is estimated on week number 13 with about 20%. Reductions of primary emissions of PM_{2.5} and NO_x are mainly due to the reduction in emissions from road traffic and contrasted by an estimated

increase in domestic heating. Modelled concentration averages between 15/03/2020 and 03/05/2020 show high reductions for NO₂, less significant variations for PM₁₀, and a potential growth of tropospheric ozone, especially in urban areas.

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Author contribution All authors contributed to the study conception, design, material preparation, data collection, and analysis. The first draft of the manuscript was written by Alessandro Marongiu and Giulia Malvestiti and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Data availability The dataset with emission estimates generated during this current study is available in the ARPA Lombardia public repository: <https://www.arpalombardia.it/sites/DocumentCenter/Documents/Aria%20-%20Relazioni%20approfondimento/Dataset%20relativo%20alle%20emissioni%20rev-maggio20.xlsx>. The datasets with air quality simulations are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate Not applicable.

Consent for publication Not applicable.

Competing interests The authors declare no competing interests.

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